





# Wound-Field Synchronous Machine-System Integration toward Increased Power Density and Commercialization



#### Presenters:

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### Overview

#### **Project Period (39 months)**

Start Date: 2019-Oct

End Date: 2022-Dec

#### **Budget**

**Total Project Funding** 

DOE: \$700,000Participants: \$170,000

Total \$870,000

#### Cumulative Program Expenditures\*

• DOE: \$ 275,857

• <u>Participants: \$ 68,965</u>

Total \$ 344,822

#### **Technology Partners**

Magna International Inc. (Recipient)

Illinois Institute of Technology (IIT) (Subrecipient)

University of Wisconsin – Madison (UW) (Subrecipient)

#### **Barriers & Technical Targets**

- Develop wound field synchronous motor demonstrating:
  - 8X increase in power density
  - Cost <= \$ 3.3/kW

#### Accomplishments

- Several WFSM architectures have been investigated using developed modeling and simulation approach
- Motor designs have been shortlisted for further electromagnetic, thermal and structural optimization
- Several cooling system architectures have been investigated using computational fluid dynamics (CFD) simulations
- One cooling system architecture has been selected Cooling jacket on the stator and jet impingement on the rotor
- Multiple versions of rotor excitation electronics have been designed, simulated, fabricated and tested.

#### **Deliverables**

- Dec. 2020 Preliminary FEA results demonstrating potential of meeting program objectives
- Dec. 2021 Completion of motor design for manufacturing
- Dec. 2022 Prototype testing and report generation

<sup>\*</sup> Total costs incurred and received thru February 2021

### **Project Objectives**

#### **Budget Period 2: January 2021 – December 2021**

# Task 2.1 – Design and optimization of the electric motor and system for automotive reliability and manufacturing

Subtask 2.1.1 – Electromagnetic analysis and optimization

Subtask 2.1.2 – Structural analysis and optimization

Subtask 2.1.3 – Thermal analysis and optimization

Subtask 2.1.4 – Analysis of field excitation system for integration into the e-drive package

### Task 2.2 – Prototyping and integration of the field excitation system

Subtask 2.2.1 – Prototyping and testing the inverter and rectifier board

Subtask 2.2.2 – Integration into the package

### Task 2.3 – Prototyping and integration of motor prototype into the package

Subtask 2.3.1 – Design of prototype e-motor complete

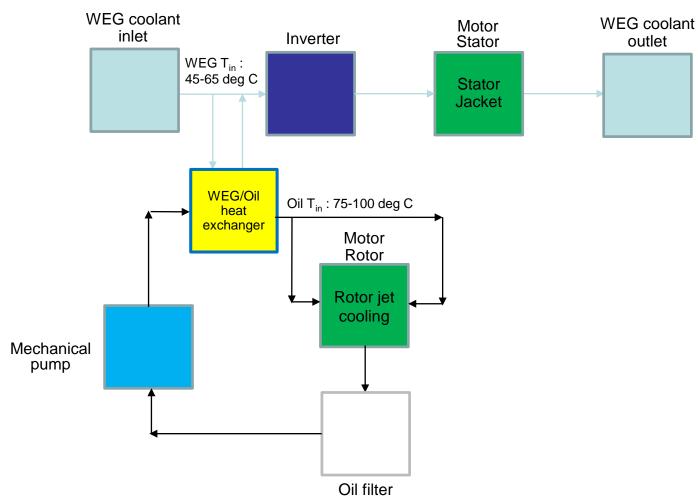
Subtask 2.3.1 – Design information, CAD models, and drawings for e-motor system ready to be transmitted for prototyping

Go/No Go

Results from finite element simulations show that the motor prototype has >= 50 kW/L power density



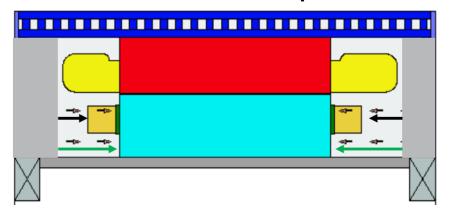
### **Motor Cooling Architecture**



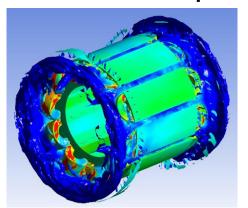
- Water Ethylene Glycol (WEG) used for stator cooling
- Oil used for rotor cooling
- Flow rates between 4L/min and 12L/min investigated for WEG
- Flow rates between 1L/min and 12 L/min investigated for oil jets
- Stator and rotor losses extracted from electromagnetic simulations
- Motor peak and continuous loading conditions included as heat loads
- CFD simulations carried performed for concept verification and optimization
- Oil inlet temperatures investigated:
  75 deg C to 100 deg C
- WEG temperatures investigated:
  45 deg C to 65 deg C



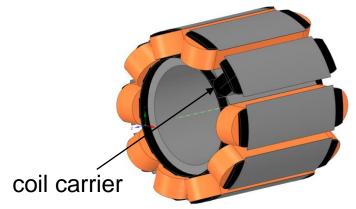
#### **Architecture selected for optimization**



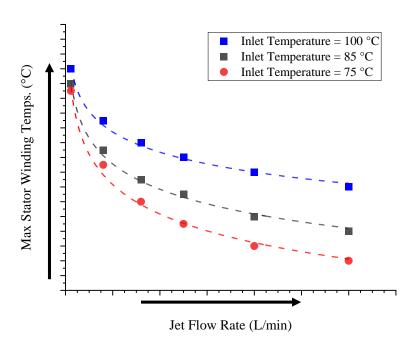
**CFD** simulations with splashing

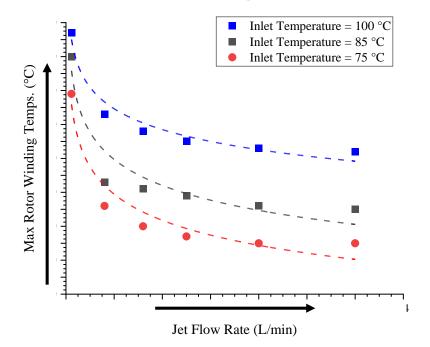


**CFD** simulations with coil carrier



Effect of oil flow rate and temperature on winding temperature





- Oil inlet temperature has significant impact compared to flow rate towards cooling the windings
- Coil carrier in the rotor provides significant thermal resistance between the jets and rotor core



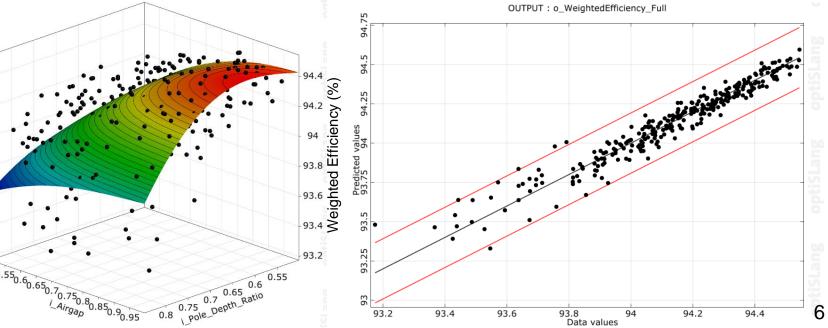
### Wound Field Synchronous Machine (WFSM) Optimization

- Direct optimization of WFSMs can take infeasible amounts of time if drive cycle efficiency is to be optimized for because of the variable field excitation
- Meta-modeling approach used with custom Python scripting to couple ANSYS optiSLang with Motor-CAD
- Stator and field currents determined to meet desired load points with iterative corrections
- Constraints on current densities, load point torque deviations, terminal voltage at each load point, maximum total rotor loss, and load point torque ripple while maximizing weighted efficiency

Large number of slot pole combinations and winding technologies explored including custom rotor

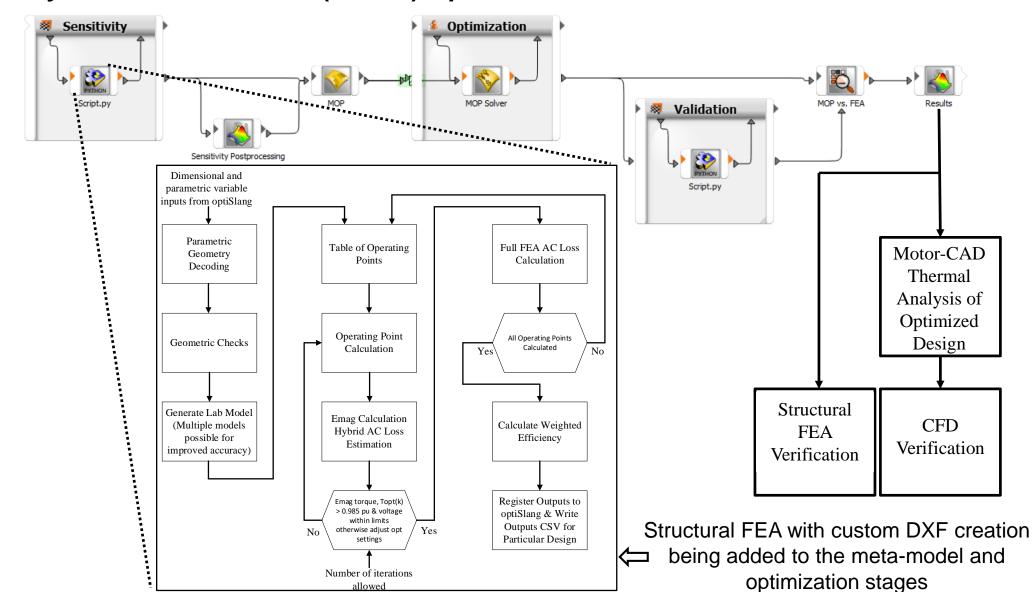
geometries

Representative metamodel (MOP) for drive cycle efficiency constructed from 300 sample designs





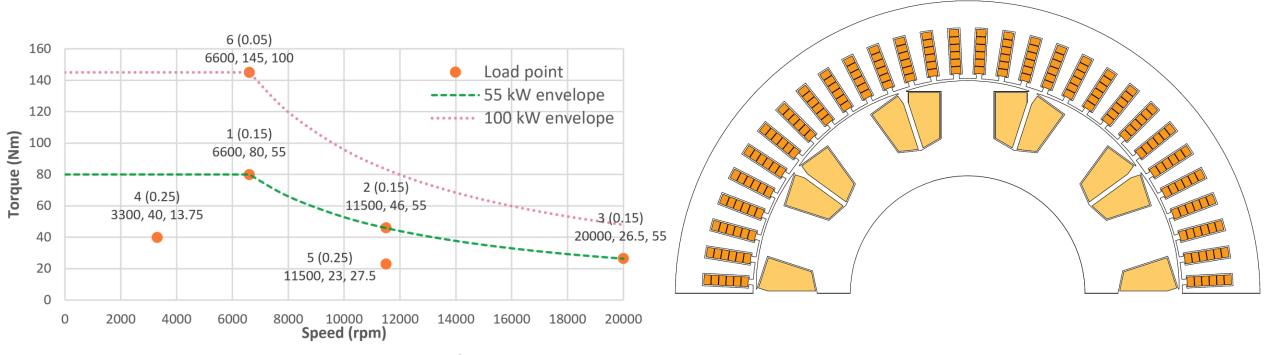
### Wound Field Synchronous Machine (WFSM) Optimization





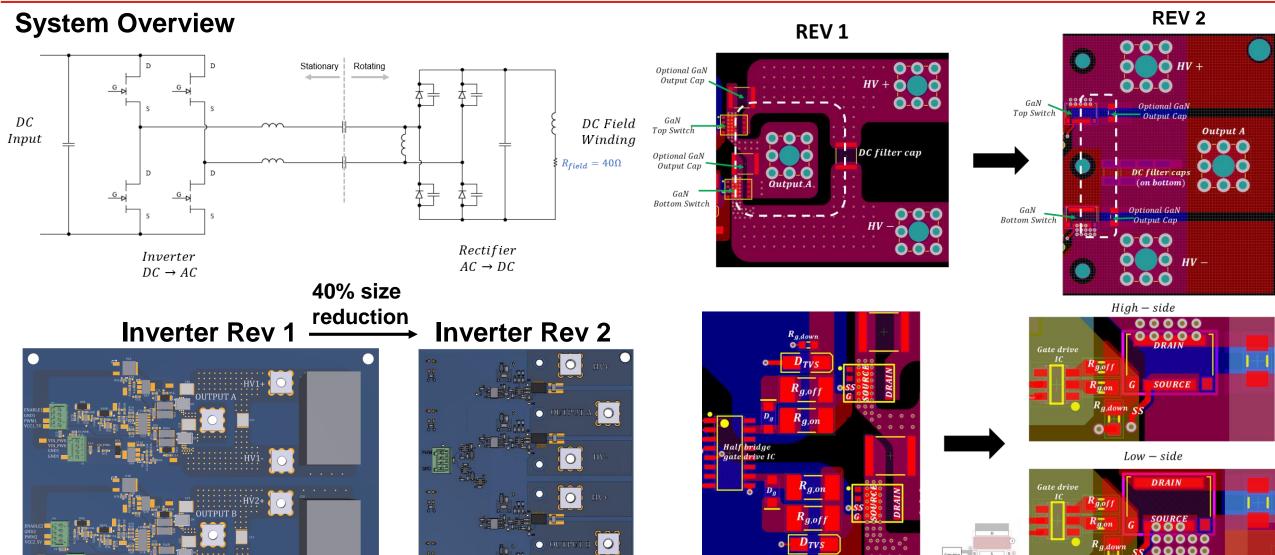
### **Representative WFSM Design**

- Different aspect ratios, motor volumes, and output powers explored given constraints on vehicle motor packaging: housings/water jackets/shafts/etc.
- Torque speed load points and power envelopes scaled with motor volume
- 50 kW/L power density target



Predicted weighted efficiency including full AC losses = 94.41%





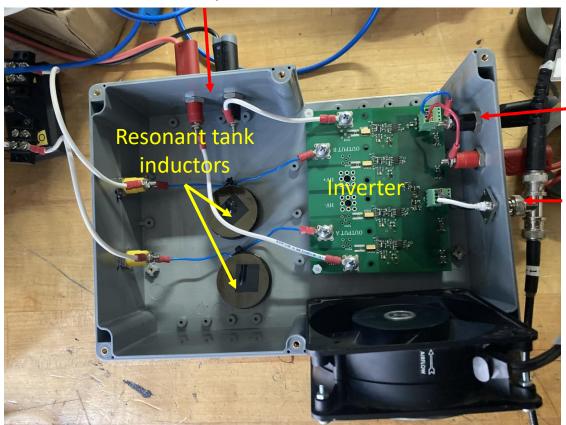
REV<sub>1</sub>

REV 2



### Rotor excitation system fabricated

**HV** Input



LV Input

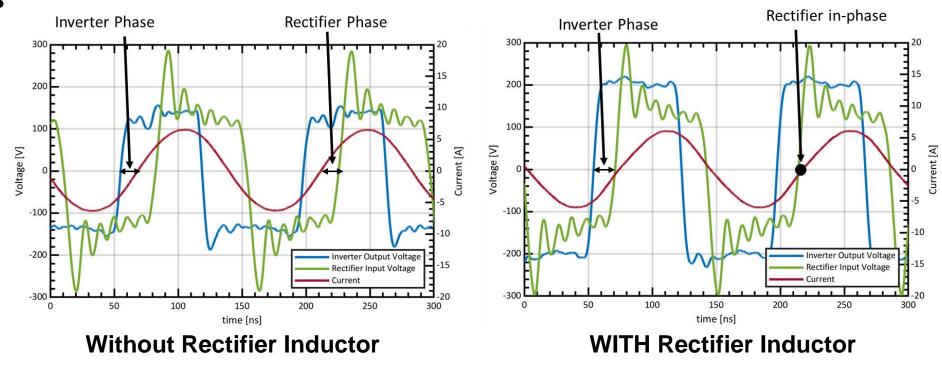
**PWM Control** 

Past university prototype Inner rotor board and rectifier

Outer stationary coupler board



### **Sample Results**



### **Summary:**

- ➤ Successful development of 6.78MHz inverter
  - ➤ Identification and elimination of ringing
  - ➤ Deadtime down to 12ns
  - ➤ Output power to 100's of Watts

#### **Conclusions:**

- ➤ All stray capacitances and inductances are important, no matter how small.
- Focus design on eliminating stray inductance in layout first, then add in components to deal with ringing

### **Team Collaboration & Coordination**

<u>Dr. Lakshmi Varaha Iyer</u> of Magna International leads the technical team comprised of <u>Prof. Ian Brown</u> of Illinois Institute of Technology and <u>Prof. Dan Ludois</u> of the University of Wisconsin-Madison

Weekly Virtual Project Meetings	Ongoing
Magna International	Motor Cooling
	Design for Manufacturing
	Prototyping and Testing
	Product & Manufacturing Requirements
University of Wisconsin-Madison	Rotor Excitation
Illinois Institute of Technology	WFSM Design

The roles of each participant are interdependent, frequent and effective communication is critical to the success of the program.

## Market Impact and Sustainability

- An 8x increase in power density provides significant weight and packaging benefits to the powertrain leading to increased EV driving range.
- The use of copper for windings and steel for laminations enable significant cost reduction of the motor active material.
- Through the removal of rare earth permanent magnets, reduced concerns over environmental footprint and commercial availability.
- High power factor through field excitation control reducing the required size of the main traction inverter (compared to IPMSMs and IMs).
- Direct field weakening and large constant power speed range (CPSR) through field excitation control.
- Potential for improved safety through field control during inverter fault conditions (compared to IPMSMs)

### Efficient use of Financial Resources

- Successful execution of a small \$870,000 project, conducted over a 39-month project period by three recipients demands the efficient use of resources and execution according to the project plan.
- The opportunity to leverage the results of the past VTO-funded WFSM research effort, as well as the research team from IIT and UW-Madison significantly increases efficiency.
- Weekly project meetings are conducted via WebEx maintaining the project focus relative to nearand long-term objectives, as well as a forum to present and address open issues in a timely manner.

### Thank You





